

ANTI-NEUTRINOS- DIRAC OR MAJORANA

Ettore Fiorini, Berkeley October 28 2005

$\nu = \nu^-$ or $\nu \neq \nu^-$

Lepton number
conservation or violation
Has neutrino a finite mass

100 % chirality

$$\begin{array}{ll} \nu & \nu^- \\ \rightarrow & \rightarrow \\ \Leftarrow & \Rightarrow \end{array}$$



The Standard Model

$$\nu_e (\bar{\nu}_e) \quad \nu_\mu (\bar{\nu}_\mu) \quad \nu_\tau (\bar{\nu}_\tau)$$

Flavor **conservation** or **violation**

Neutrino oscillations need $m_\nu \neq 0$

$$\nu_e \longrightarrow \nu_\mu$$

$$\nu_e \longrightarrow \nu_\tau$$

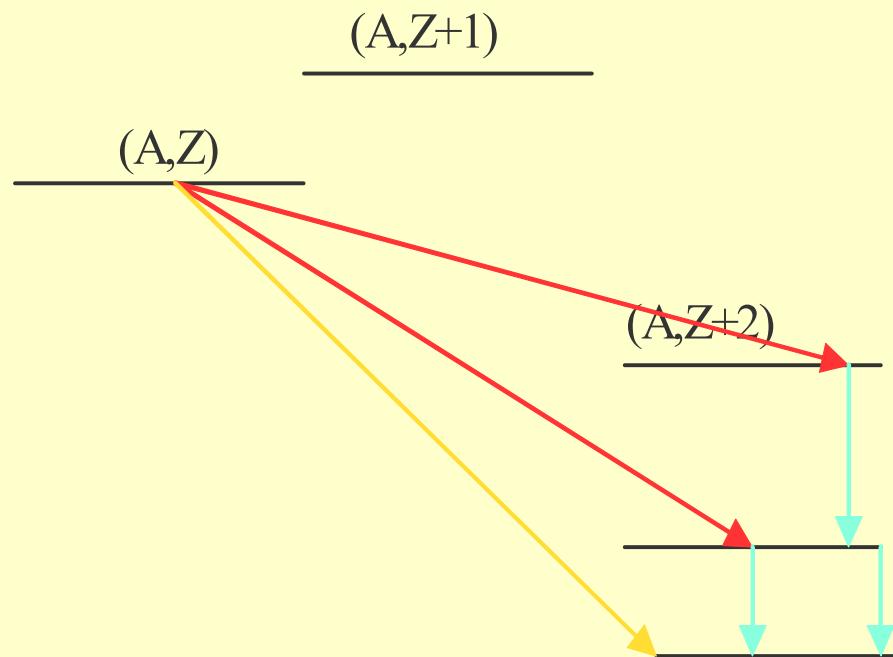
$$P(\nu_a - \nu_b) - > \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m_{ab}^2 (\text{eV}^2) L(\text{km})}{E (\text{GeV/MeV})})$$

Oscillations have been found in solar, atmospheric and reactor neutrino experiments, but only indicate that

$$m_\nu^2 \neq 0$$

to determine $\langle m_\nu \rangle \Rightarrow$ neutrinoless double beta decay

1. $(A, Z) \Rightarrow (A, Z+2) + 2 e^- + 2 \bar{\nu}_e$
2. $(A, Z) \Rightarrow (A, Z+2) + 2 e^- + \chi \dots (2, 3 \chi)$
3. $(A, Z) \Rightarrow (A, Z+2) + 2 e^-$



Double Beta –Disintegration

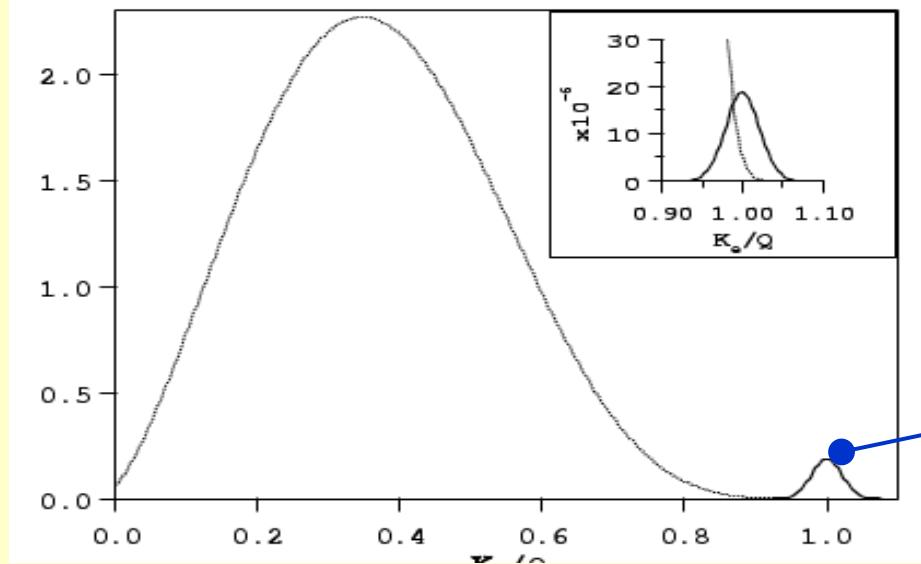
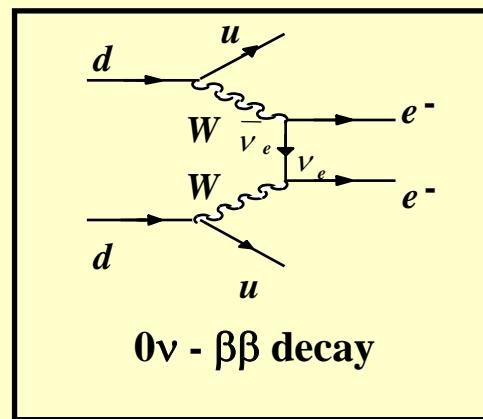
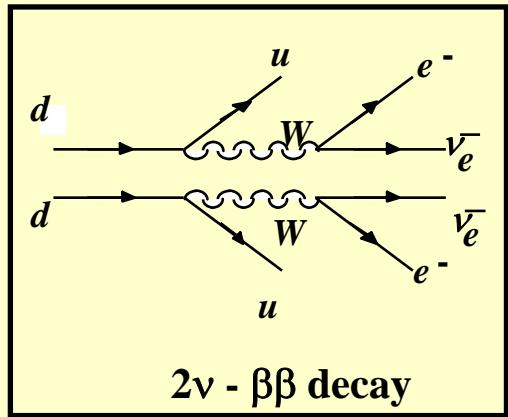
M.Goeppert-Mayer, *The John Hopkins University*

(Received May, 20 , 1935)

From the **Fermi theory** of $\beta-$ disintegration the probability of simultaneous emission of two electrons (**and two neutrinos**) has been calculated. The result is that this process occurs **sufficiently rarely** to allow **an half-life of over 10^{17} years** for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass

Since the very beginning double beta decay was considered as a powerful tool **to test lepton number conservation**. Many experiments were carried out sometimes with later disproved evidences. First evidences in geochemical experiments and for the first time with a direct experiment by

M.Moe et al for ${}^{82}\text{Se}$



Neutrinoless $\beta\beta$ decay

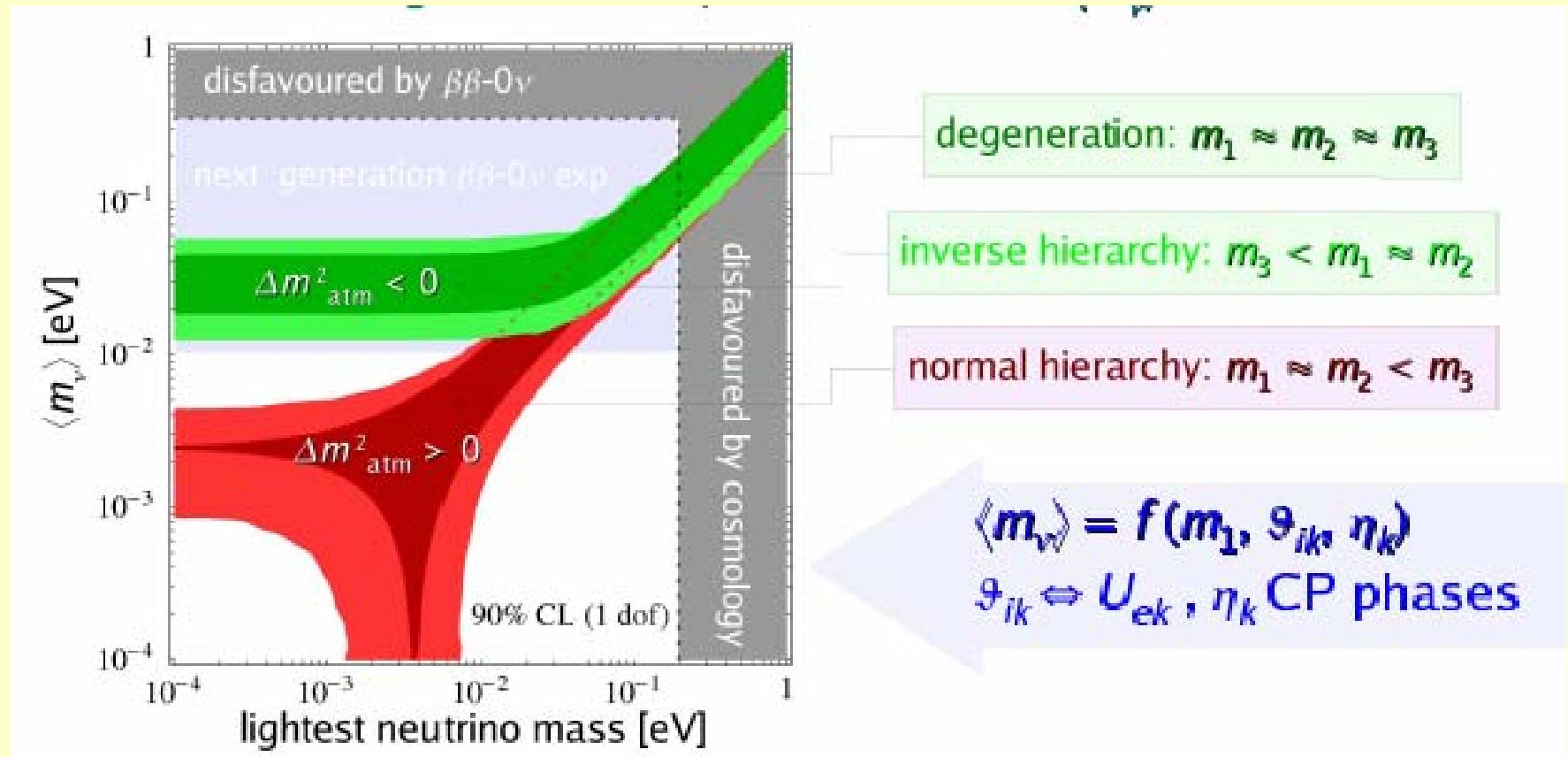
Solar, atmospheric and reactor neutrino oscillation experiments indicate that
 $D_{mn} \neq 0 \Rightarrow$ need to determine the absolute neutrino mass
 Direct experiments on b decay $\Rightarrow m_n < 2.2$ eV KATRIN .35-2 Results
 of WMAP and 2dF Galaxy Redshift Survey $\Rightarrow S m_n < 0.7$ eV

$$1/\tau = G(Q, Z) |M_{\text{nucl}}|^2 \langle m_\nu \rangle^2$$

rate of DDB-0ν Phase space Nuclear matrix elements Effective Majorana neutrino mass

Need to search for neutrinoless DBD in various nuclei
 A pick could be due to some unforeseen background peak

Neutrinoless $\beta\beta$ decay would imply a non zero effective majorana neutrino mass as indicated by oscillation experiments



Experimental approaches

Geochemical experiments

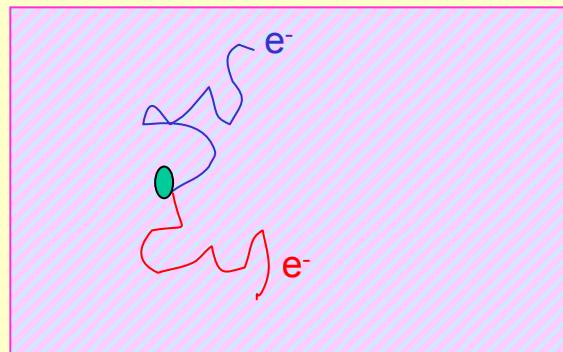
$^{182}\text{Se} = > ^{82}\text{Kr}$, $^{96}\text{Zr} = > ^{96}\text{Mo}$ (?) , $^{128}\text{Te} = > ^{128}\text{Xe}$ (non confirmed), $^{130}\text{Te} = > ^{130}\text{Te}$

Radiochemical experiments

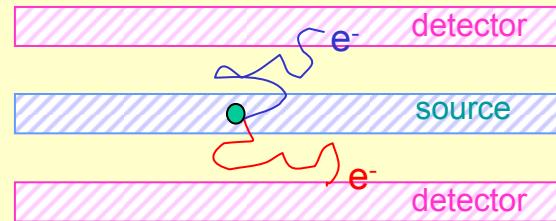
$^{238}\text{U} = > ^{238}\text{Pu}$ (non confirmed)

Direct experiments

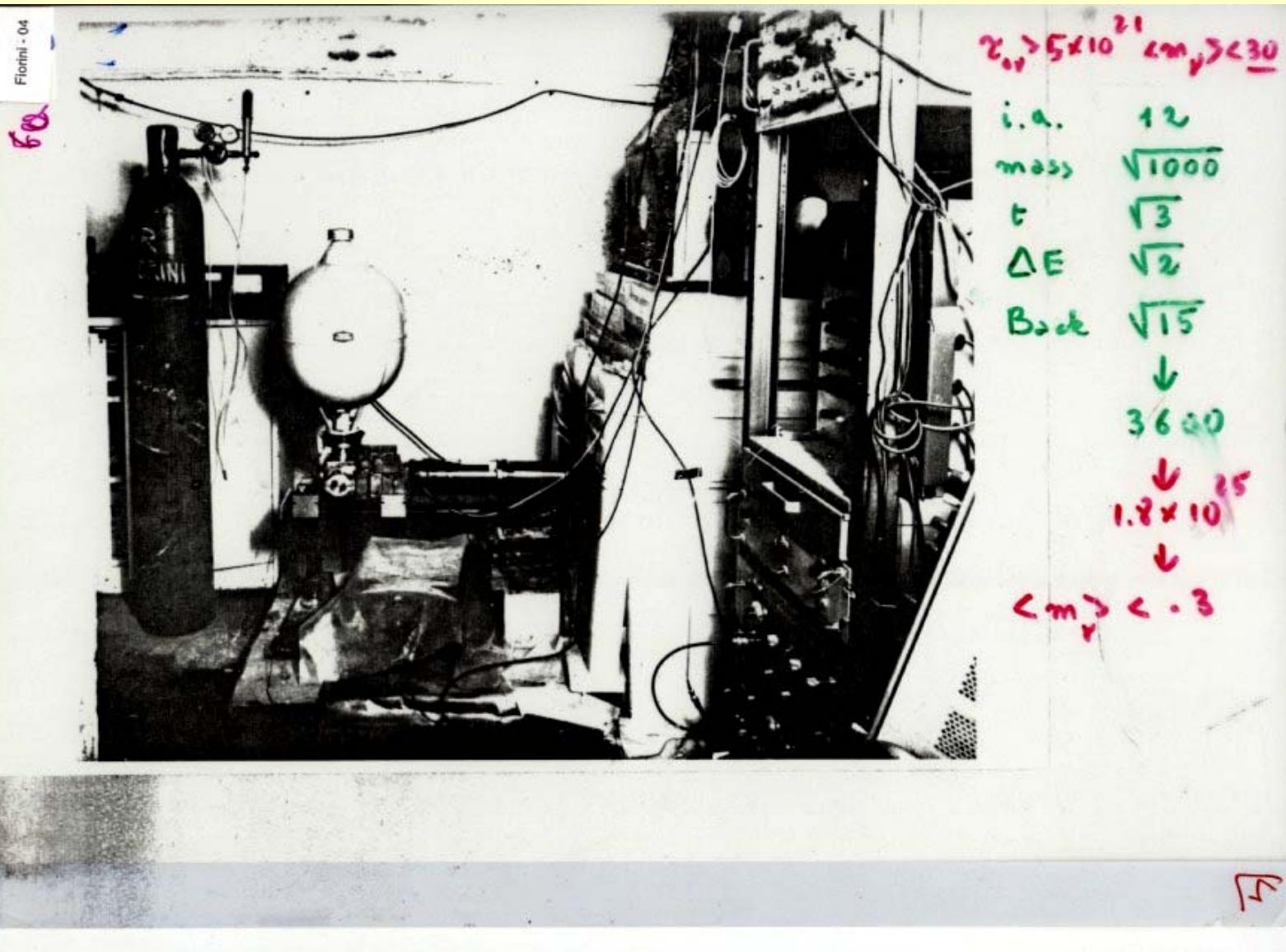
Source = detector
(calorimetric)



Source \neq detector



Source \neq Detector

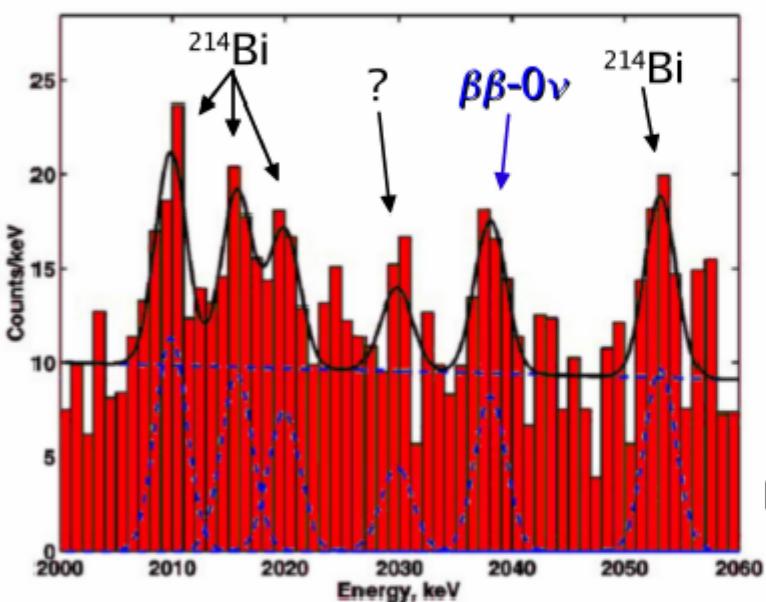


Present experimental situation

Nucleus	Experiment	%	$Q_{\beta\beta}$	Enr	Technique	T_{0v} (y)	$\langle m_v \rangle$
^{48}Ca	Elegant IV	0.19	4271		scintillator	$>1.4 \times 10^{22}$	7-45
^{76}Ge	Heidelberg-Moscow	7.8	2039	87	ionization	$>1.9 \times 10^{25}$.12 - 1
^{76}Ge	IGEX	7.8	2039	87	Ionization	$>1.6 \times 10^{25}$.14 – 1.2
^{76}Ge	Klapdor et al	7.8	2039	87	ionization	1.2×10^{25}	.44
^{82}Se	NEMO 3	9.2	2995	97	tracking	$>1. \times 10^{23}$	1.8-4.9
^{100}Mo	NEMO 3	9.6	3034	95-99	tracking	$>4.6 \times 10^{23}$.7-2.8
^{116}Cd	Solotvina	7.5	3034	83	scintillator	$>1.7 \times 10^{23}$	1.7 - ?
^{128}Te	Bernatovitz	34	2529		geochem	$>7.7 \times 10^{24}$.1-4
^{130}Te	Cuoricino	33.8	2529		bolometric	$>2 \times 10^{24}$.2-1.
^{136}Xe	DAMA	8.9	2476	69	scintillator	$>1.2 \times 10^{24}$	1.1 - 2.9
^{150}Nd	Irvine	5.6	3367	91	tracking	$>1.2 \times 10^{21}$	3 - ?

Heidelberg-Moscow exp.: evidence for $\beta\beta$ -0 ν of ^{76}Ge

- best exploitation of the Ge detector technique proposed by E. Fiorini in 1960
 - ▶ longest running experiment (13 years) with largest exposure (71.7 kg \times y)
 - ▶ Status-of-the-art for low background techniques and for enriched Ge detectors
 - ▶ reference for all last generation $\beta\beta$ -0 ν experiments



1990 – 2003 data, all 5 detectors
exposure = 71.7 kg \times y

$$\tau_{\frac{1}{2}^{0\nu}} = 1.2 \times 10^{25} \text{ years}$$

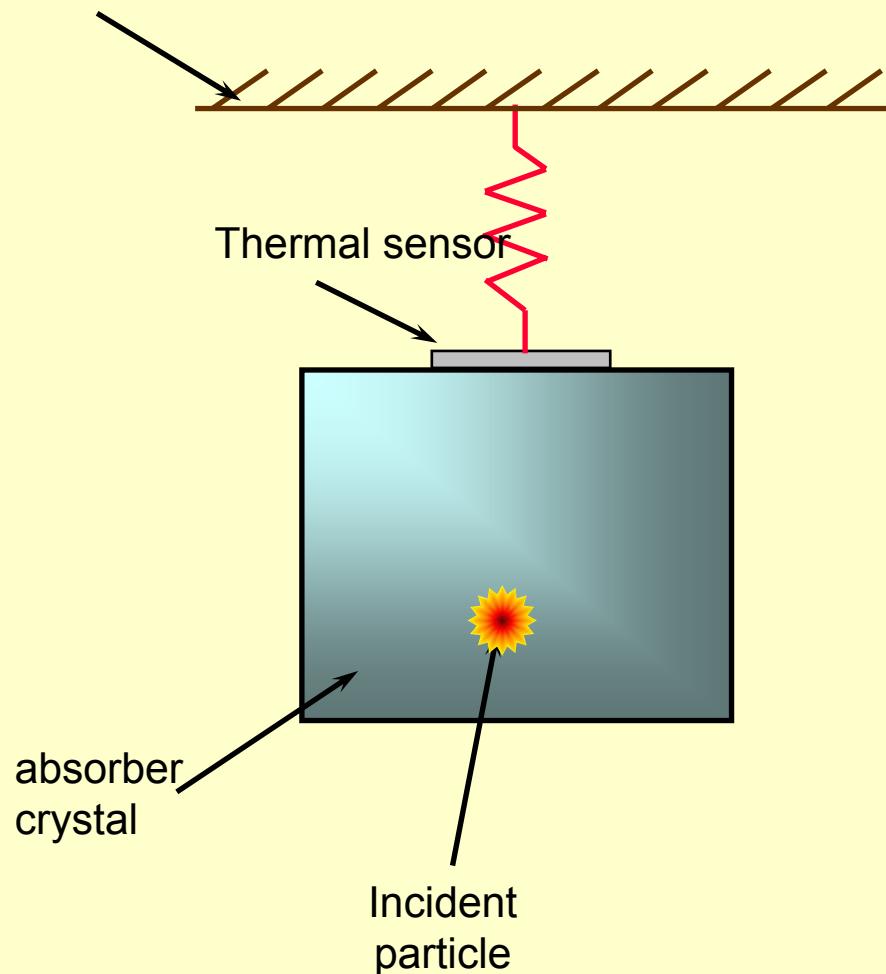
$$\langle m_\nu \rangle = 0.44 \text{ eV}$$

H.V.Klapdor-Kleingrothaus *et al.*, Phys. Lett. B 586 (2004) 198

- still, community **does not fully accept the result**, because:
 - ▶ signal is indeed **too faint** (4σ) to be *blindly* accepted: people still find some weak points in the published analysis
 - ▶ presence of **not understood peaks** around the signal and with *similar* significance
 - ▶ impossibility to check an **energy window** larger than the published one
- nevertheless any future $\beta\beta$ -0 ν experiment will have to cope with this result

Cryogenic detectors

heat bath

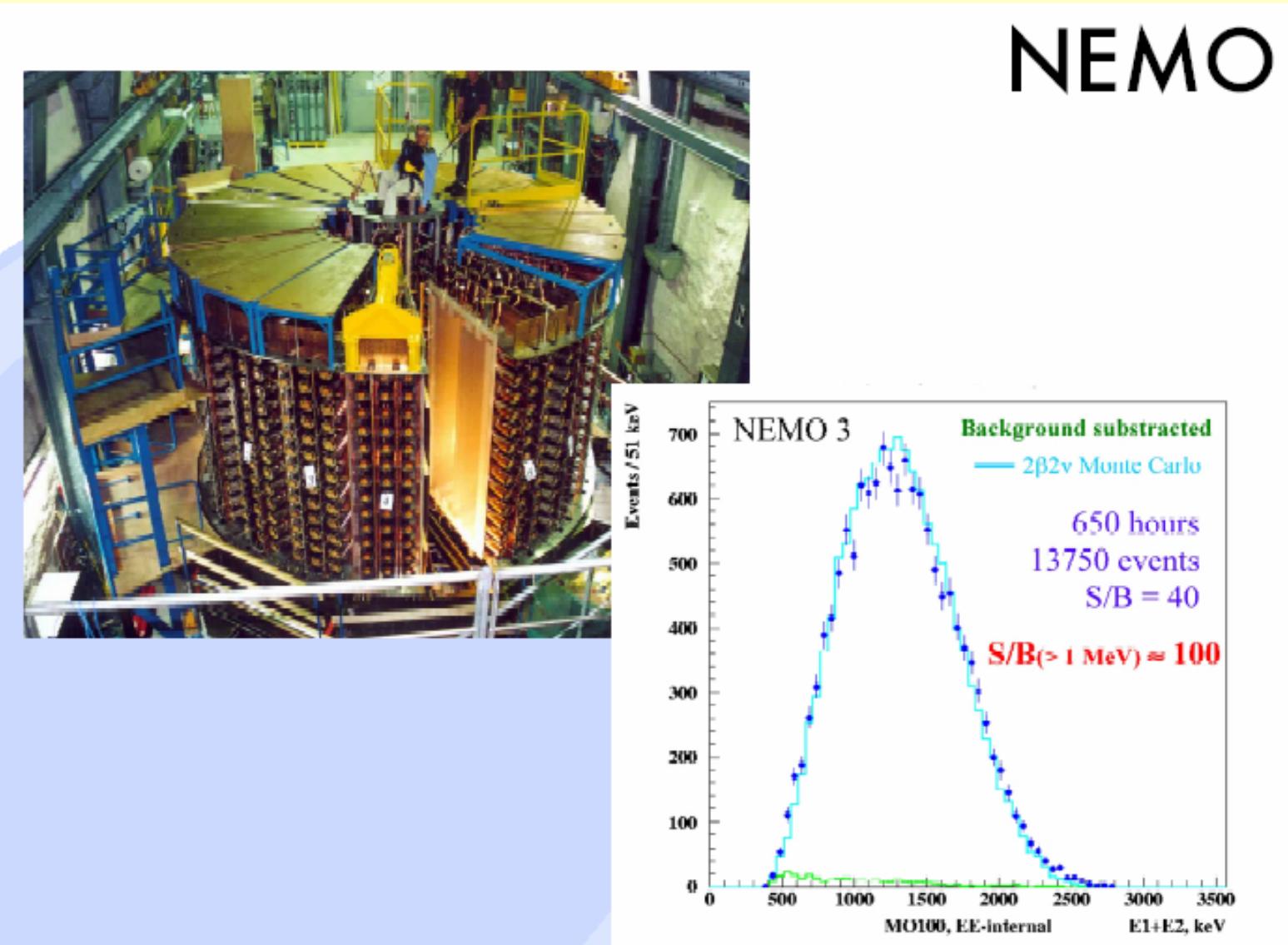


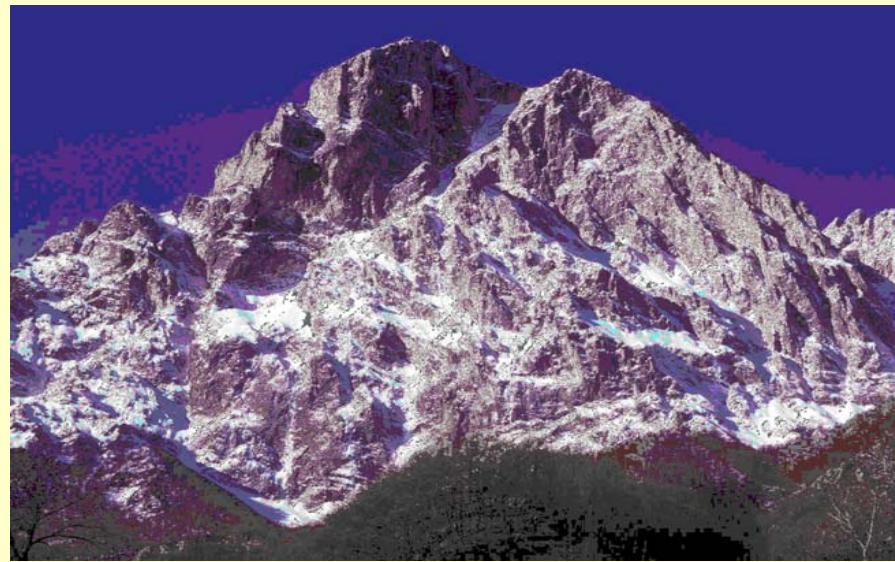
$$CV = 1944 \left(\frac{V}{Vm} \right) \left(\frac{T}{TD} \right)^3 J/K$$

$$\Delta E = \xi \sqrt{k C_V T^2}$$

	ΔE		
@ 5 keV	$\sim 100 \text{ mk}$	$\sim 1 \text{ mg}$	<1 eV $\sim 3 \text{ eV}$
@ 2 MeV	$\sim 10 \text{ mk}$	$\sim 1 \text{ kg}$	<10 eV $\sim \text{keV}$

Two new experiments NEMO III e CUORICINO



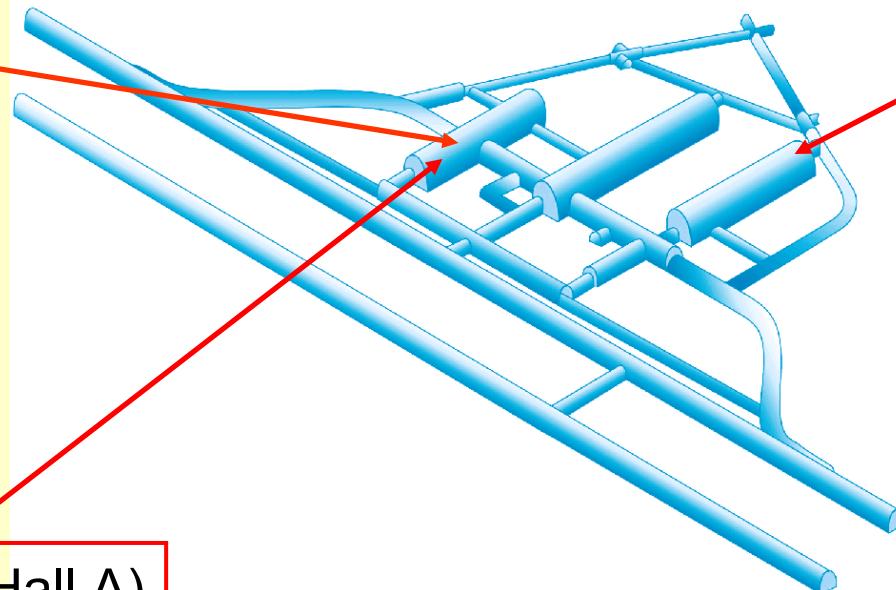


Searches with
thermal detectors

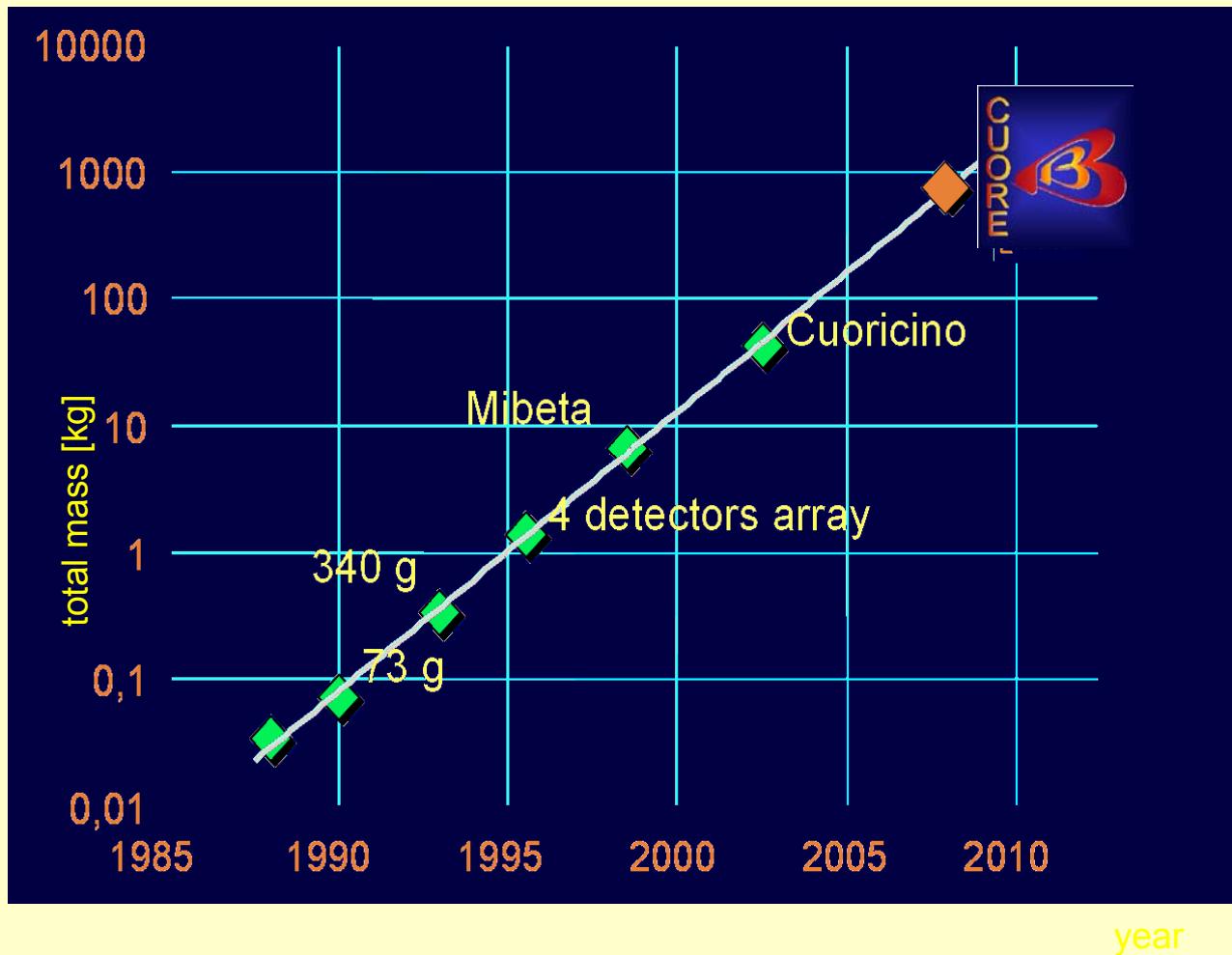
CUORE (Hall A)

CUORE R&D (Hall C)

Cuoricino (Hall A)



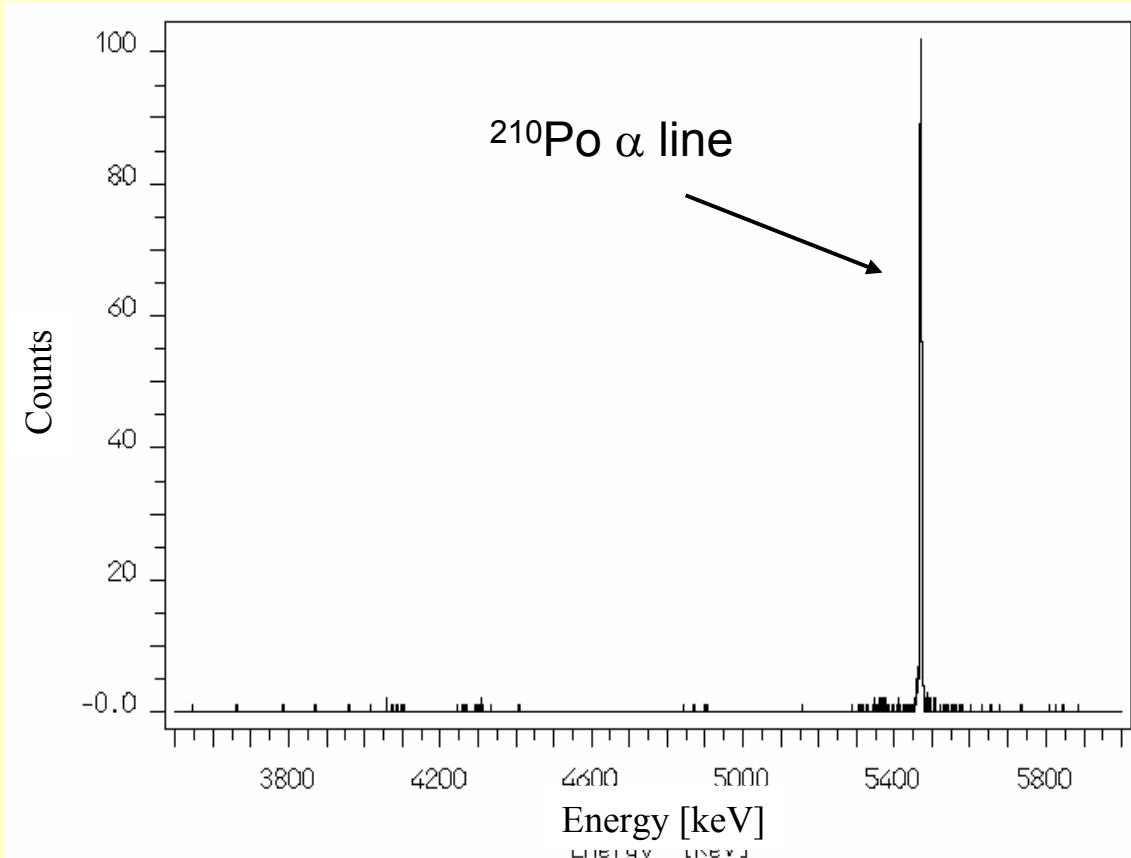
Crescita della massa dei bolometri

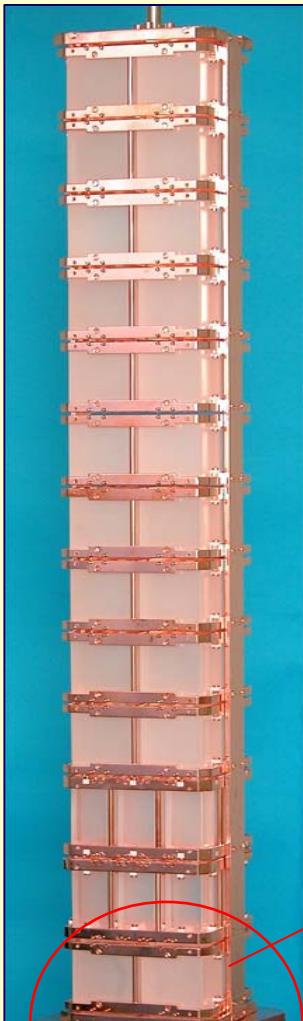


Resolution of the 5x5x5 cm³ (~ 760 g) crystals

- 0.8 keV FWHM @ 46 keV
- 1.4 keV FWHM @ 0.351 MeV
- 2.1 keV FWHM @ 0.911 MeV
- 2.6 keV FWHM @ 2.615 MeV
- 3.2 keV FWHM @ 5.407 MeV

(the best α spectrometer ever realized)

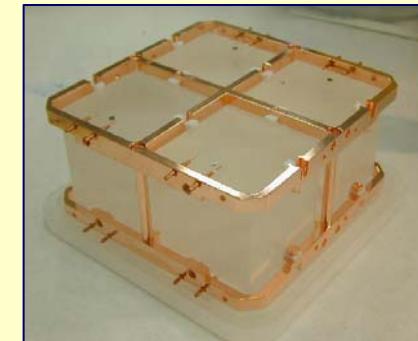




- ✓ Search for the $2\beta|_{\text{ov}}$ in ^{130}Te ($Q=2529$ keV) and other rare events
- ✓ At Hall A in the Laboratori Nazionali del Gran Sasso (LNGS)
- ✓ 18 crystals $3 \times 3 \times 6$ cm 3 + 44 crystals $5 \times 5 \times 5$ cm 3 = **40.7 kg of TeO₂**
- ✓ Operation started in the beginning of 2003 => ~ 4 months
- ✓ **Background $.18 \pm .01$ c /kev/ kg/ a**
- ✓ $T_{1/2}^{0\nu} (^{130}\text{Te}) > 2 \times 10^{24}$ y $\langle m_\nu \rangle .2 - 1.$



Klapdor 0.1 – 0.9

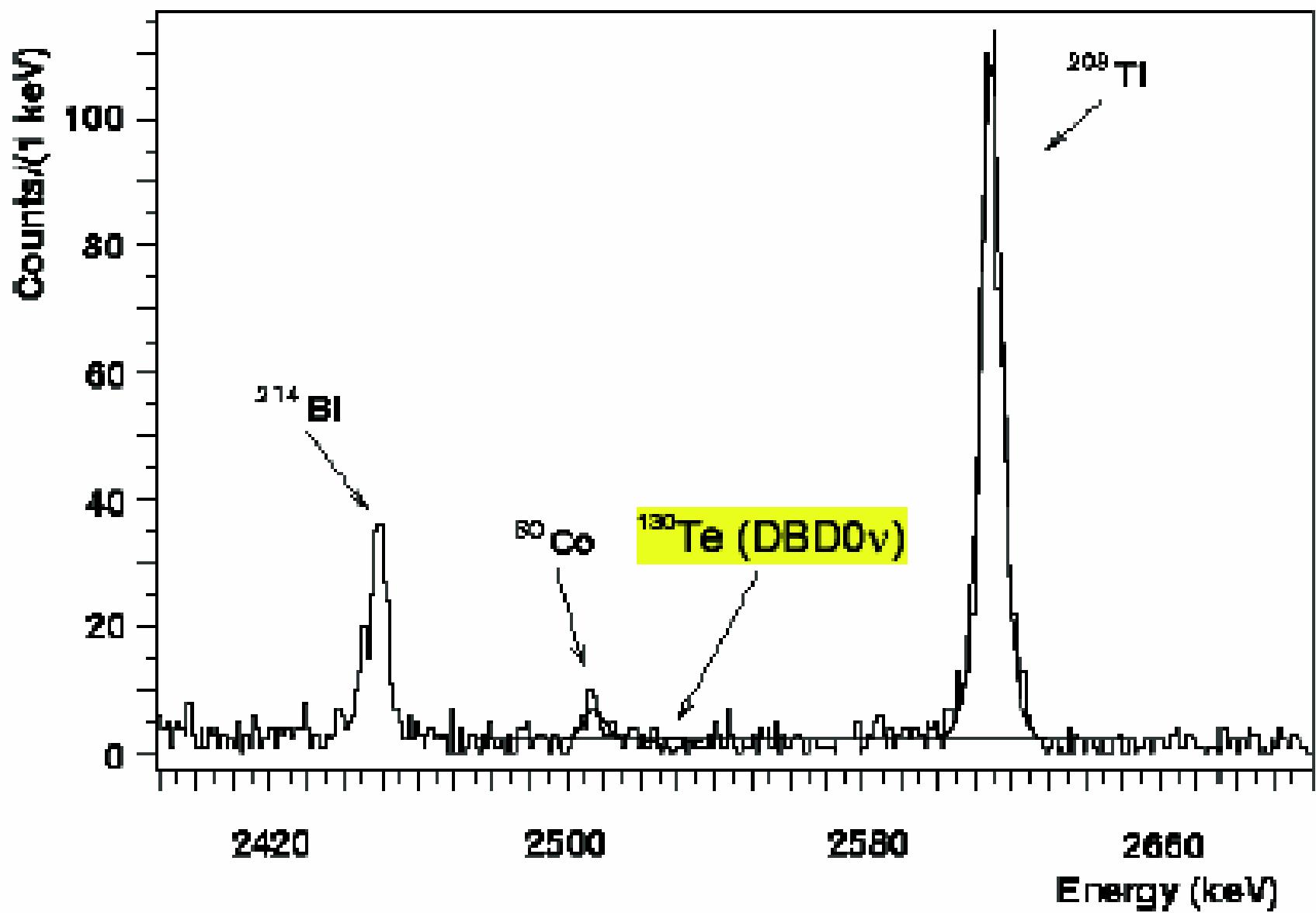


2 modules, 9 detector each,
crystal dimension $3 \times 3 \times 6$ cm 3
crystal mass **330 g**
 $9 \times 2 \times 0.33 = 5.94$ kg of TeO₂

11 modules, 4 detector each,
crystal dimension $5 \times 5 \times 5$ cm 3
crystal mass **790 g**
 $4 \times 11 \times 0.79 = 34.76$ kg of TeO₂

Tower assembling



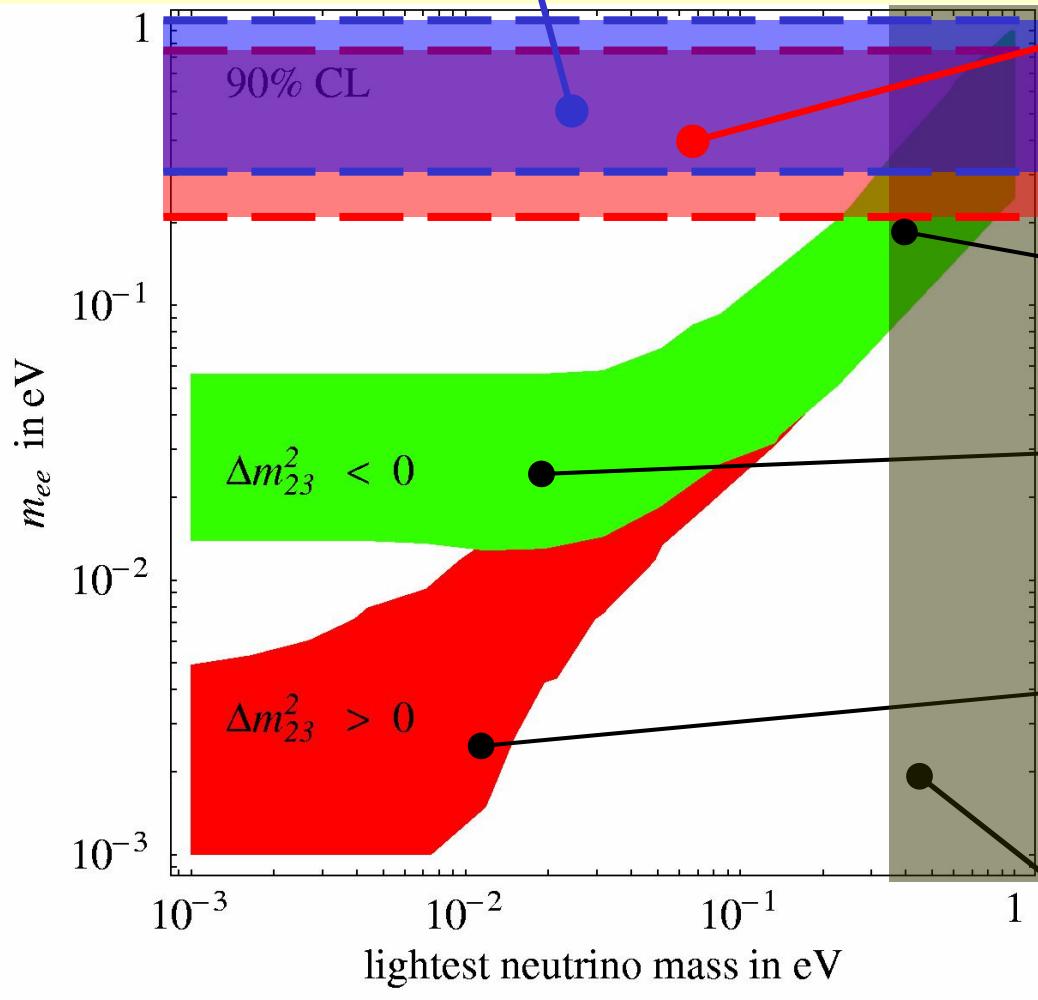


DBD and Neutrino Masses

Present Cuoricino region

Arnaboldi et al., submitted to PRL, hep-ex/0501034

(2005).



Possible evidence

(best value 0.39 eV)

H.V. Klapdor-Kleingrothaus et al., Nucl.Instrum.and
Meth. ,522, 367 (2004).

With the same matrix elements the
Cuoricino limit is **0.53 eV**

“quasi” degeneracy
 $m_1 \approx m_2 \approx m_3$

Inverse hierarchy
 $\Delta m^2_{12} = \Delta m^2_{atm}$

Direct hierarchy
 $\Delta m^2_{12} = \Delta m^2_{sol}$

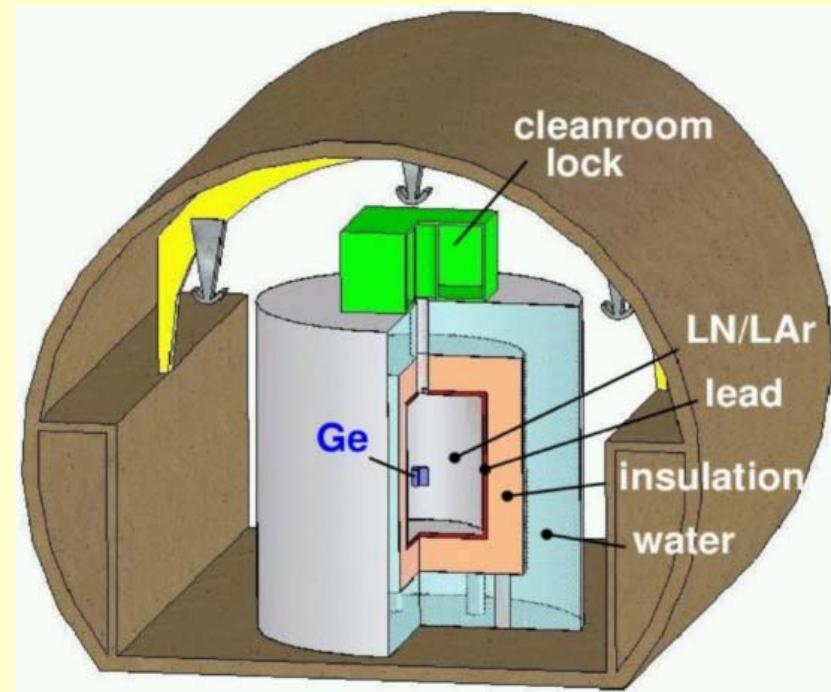
Cosmological disfavoured
region (WMAP)

Next generation experiments

Name		%	$Q_{\beta\beta}$	% E	B c/y	T (year)	Tech	<m>
CUORE	^{130}Te	34	2533	90	3.5	1.8×10^{27}	Bolometric	9-57
GERDA	^{76}Ge	7.8	2039	90	3.85	2×10^{27}	Ionization	29-94
Majorana	^{76}Ge	7.8	2039	90	.6	4×10^{27}	Ionization	21-67
GENIUS	^{76}Ge	7.8	2039	90	.4	1×10^{28}	Ionization	13-42
Supernemo	^{82}Se	8.7	2995	90	1	2×10^{26}	Tracking	54-167
EXO	^{136}Xe	8.9	2476	65	.55	1.3×10^{28}	Tracking	12-31
Moon-3	^{100}Mo	9.6	3034	85	3.8	1.7×10^{27}	Tracking	13-48
DCBA-2	^{150}Nd	5.6	3367	80		1×10^{26}	Tracking	16-22
Candles	^{48}Ca	.19	4271	-	.35	3×10^{27}	Scintillation	29-54
CARVEL	^{48}Ca	.19	4271	-		3×10^{27}	Scintillation	50-94
GSO	^{160}Gd	22	1730	-	200	1×10^{26}	Scintillation	65-?
COBRA	$\underline{^{115}\text{Cd}}$	7.5	2805				Ionization	
SNOLAB+	^{150}Nd	5.6	3367				Scintillation	

IONIZATION

- **goal:** analyse HM evidence in a short time using existing ^{76}Ge enriched detectors (HM, Igex)
- approach similar to GENIUS but less LN2
 - **naked Ge crystals in LN2 or LAr**
- more compact than GENIUS
 - 1.5 m LN2(LAr) + 10 cm Pb + 2 m water
 - 2-3 orders of magnitude better bkg than present Status-of-the-Art
 - active shielding with LAr scintillation
- 3 phases experiment
- **Phase I:**
 - radioactivity tests
 - $\approx 20 \text{ kg } ^{76}\text{Ge}$ from HM and Igex
 - expected bkg □ 0.01 c/keV/kg/y (intrinsic)
 - check at 5σ HM evidence
 - 15 kg \times y □ 6 ± 1 □□ events on 0.5 bkg events
- **Phase II:**
 - add new enriched segmented detectors with special care for activation
 - expected background $\approx 0.001 \text{ c/keV/kg/y}$
 $2 \times 10^{26} \text{ y}$ with 100 kg \times y
 $\langle m \rangle 0.09 \div 0.29 \text{ eV}$
- **Phase III:** $\langle m \rangle 0.01 \text{ eV}$ with 1 ton Ge
 - worldwide collaboration



- Approved by LNGS S.C.
- site: Hall A northern wing
- funded 40 kg enriched ^{76}Ge for phase II
- aggressive time schedule

MAJORANA

Aalseth CE et al. hep-ex/0201021



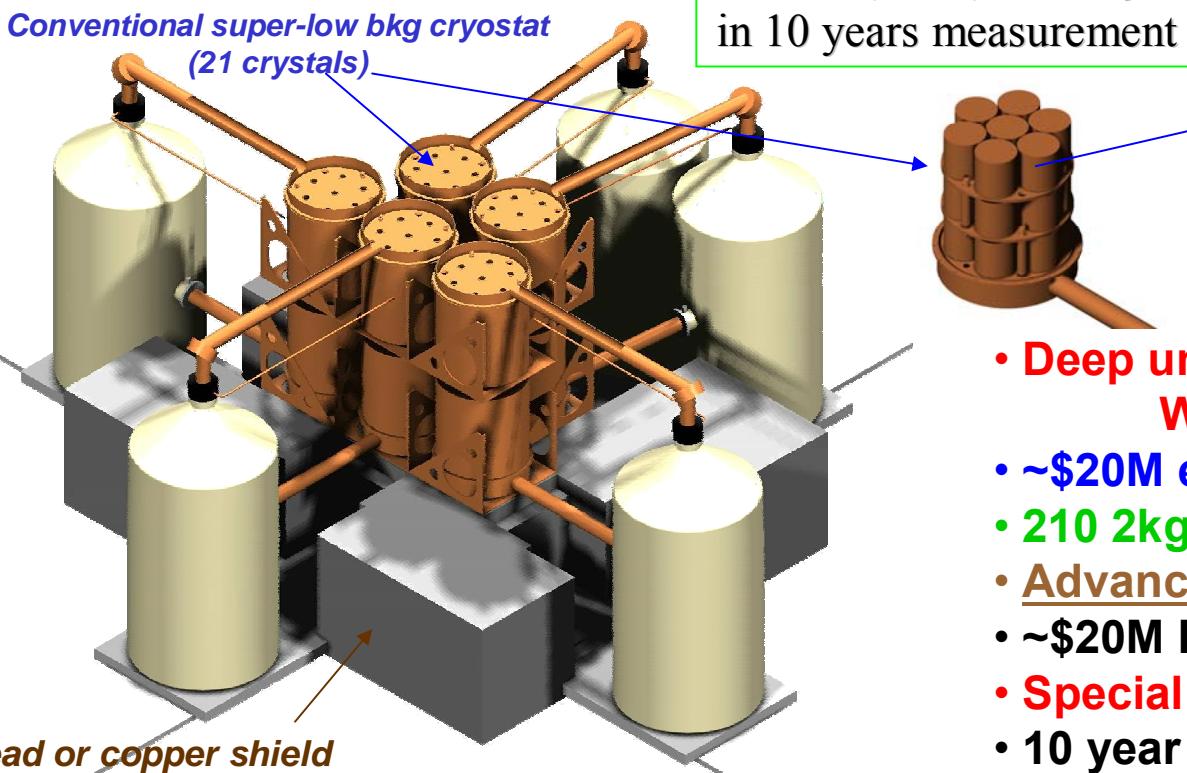
PNNL
South Carolina University
TUNL
ITEP
Dubna
NMSU
Washington University

GOAL: $\langle m_\nu \rangle \sim 0.02\text{-}0.07 \text{ eV}$

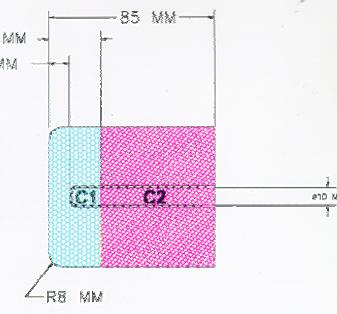
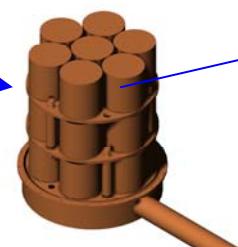
Main concern:

- cost and time for i.e. ^{76}Ge
- cosmogenic background
- material selection

Perkin-Elmer design
PT6X2
12-SEGMENTS
SEGMENTED DETECTOR
(6-EXTERNAL X 2-INTERNAL)



$T^{0\nu} > (0.4\text{-}2) \times 10^{28} \text{ y}$
in 10 years measurement



8 SIDE CHANNELS
2 CENTER CHANNELS
TOTAL = 8 PREAMPLIFIERS

- Deep underground location
WIPP/Homestake
- ~\$20M enriched 85% ^{76}Ge
- 210 2kg crystals, 12 segments
- Advanced signal processing
- ~\$20M Instrumentation
- Special materials (low bkg)
- 10 year operation

Majorana

White paper nucl-ex/0311013

- concept: cosmogenics main background source (IGEX)
 - 500 kg Ge crystals in ultra low background cryostats
 - segmentation and PSD to reduce bkg
- 2 experimental phases: 180 kg → 500 kg

■ Phase I:

- 180 kg 86% ^{76}Ge (centrifugation)

- Modules with 57 crystals each (40 cm x 40 cm Cryostat)

- Three modules for 180 kg

- Eight modules for 500 kg (phase II)

- Maximal use of copper electroformed underground

- Background rejection methods

- Granularity

- Pulse Shape Discrimination

- Single Site Time Correlation

- Detector Segmentation

- Underground Lab

- 6000 mwe

- Class 1000

FULL EXPERIMENT

(9 years from start in 2006)

- expected bkg 1.21 c/ton/y in ROI
- mainly Th from Cu structure

- $\tau_{1/2}$ □ $4 \cdot 10^{26}$ y in 3 years

- $\langle m \rangle$ □ $0.07 \div 0.21$ eV

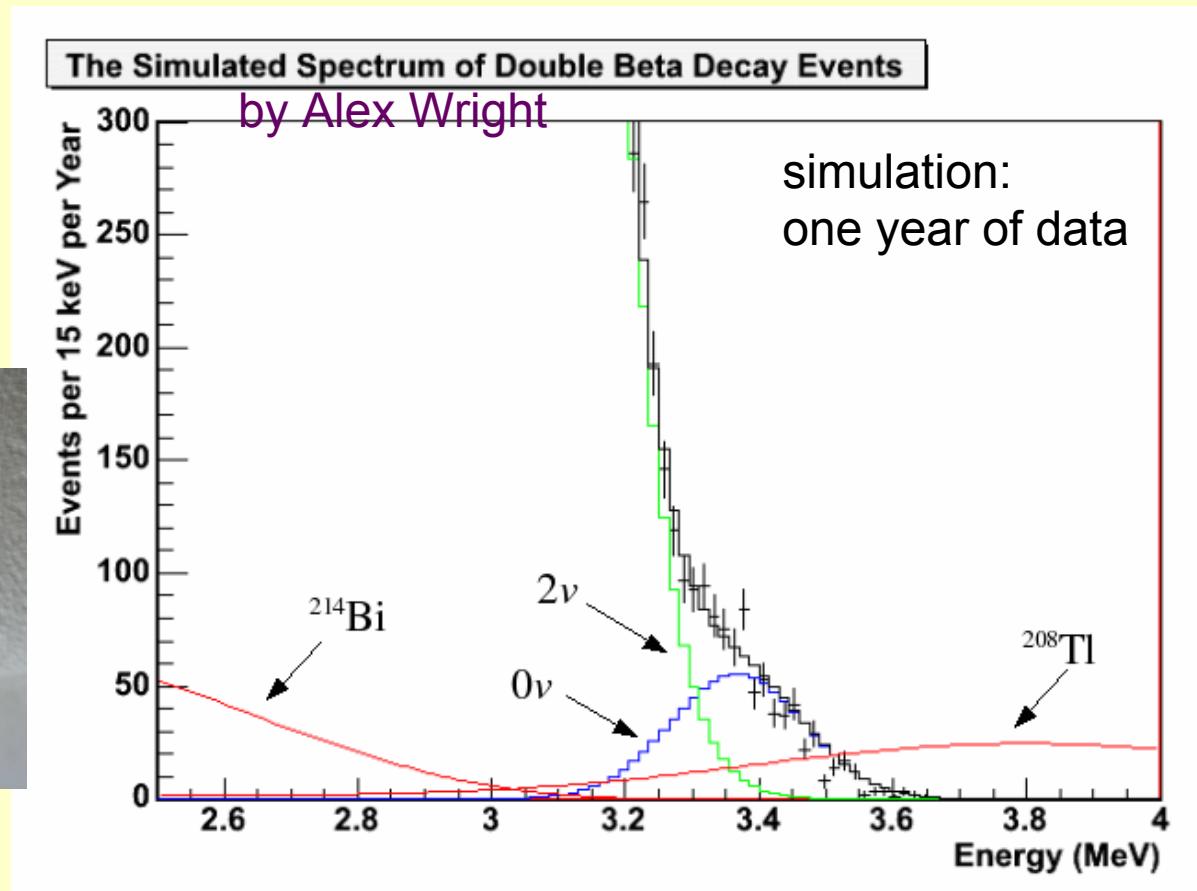
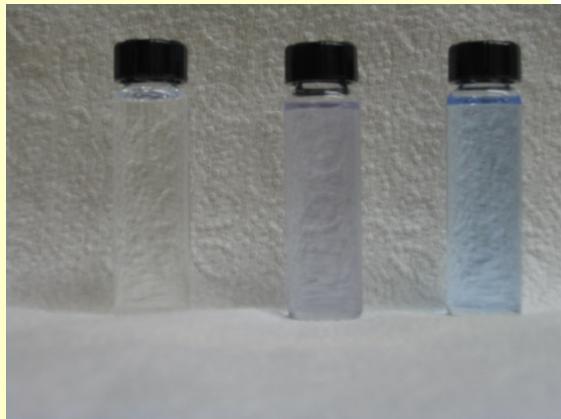
Scintillation

X-MASS



Scintillation Nd dissolved in SNO => tons of material;

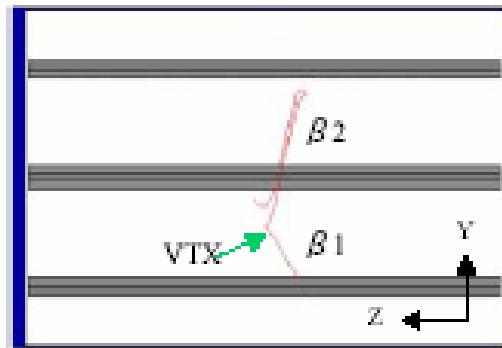
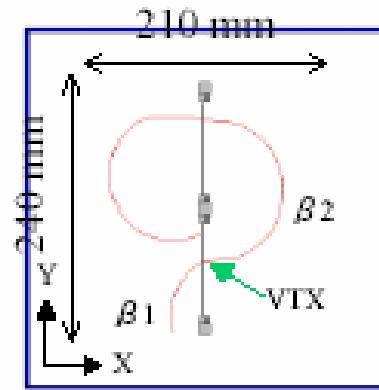
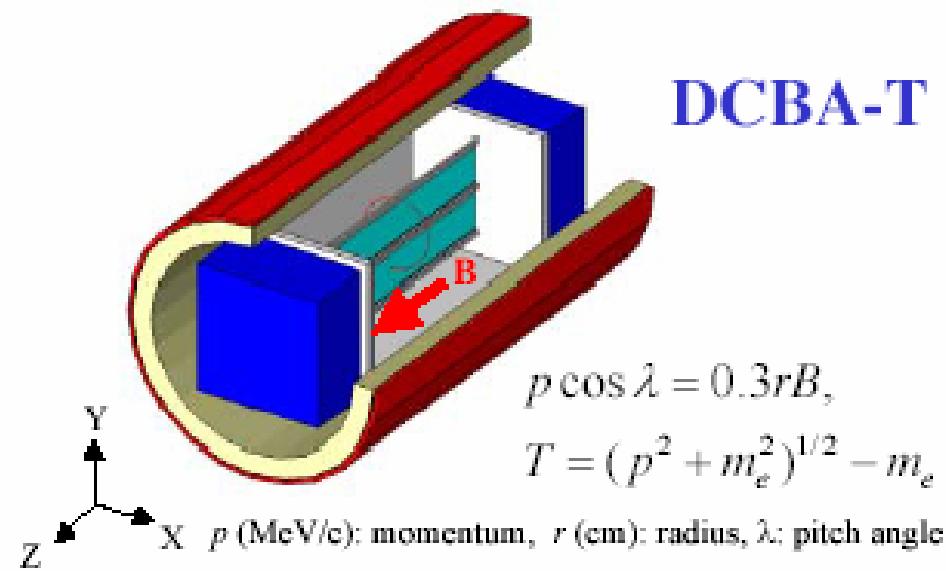
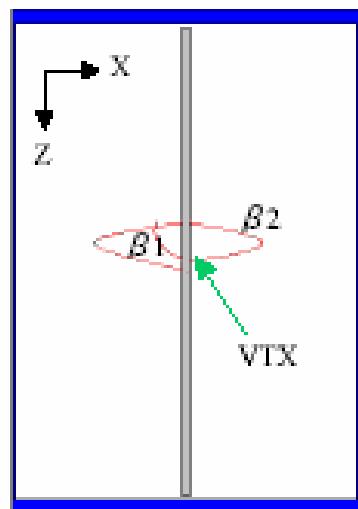
- On: 1000 events per
- year with 1%



*maximum likelihood statistical test of the shape to extract
0ν and 2ν components...~240 units of $\Delta\chi^2$ significance after only 1 year!*

Tracking

○ ● ● DCBA



Tracking

- concept: scale NEMO setup
- tracking calorimeter
- already tested technology (NEMO)
 - ▶ event topology (Detection of the 2 electrons)
 - ▶ single and sum energy + angular correlation
 - ▶ particle identification
 - ▶ Background control
- source purification
- background level measurement
- external background reduction (Rn)
 - No strong theoretical criteria for isotope selection: ^{82}Se
 - ▶ transition energy: 2 995 keV
 - ▶ natural i.a.: 8.7%

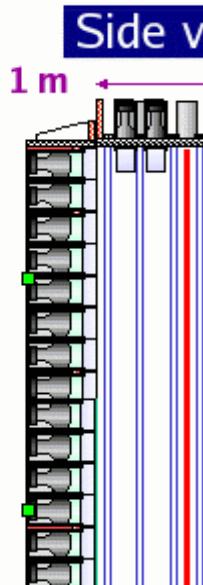
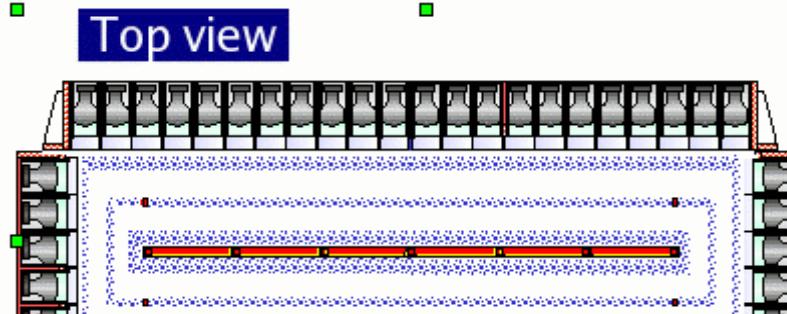
**3 years R&D aiming at a 50 meV $\langle m_{\nu} \rangle$
sensitivity: accepted by IN2P3 s.c.**

- 5 kg of ^{82}Se funded by ILIAS (Europe)
- Enrichment:
 - 1 kg of ^{82}Se in 2005
 - 2 kg of ^{82}Se in 2006
 - 5 kg of ^{82}Se in 2007

SuperNemo

- Planar geometry
 - ▶ source (40 mg/cm^2): 12 m^2
 - ▶ tracking volume: ~3000 channels
 - ▶ calorimeter: ~1000 PMT
- Modular:
 - ▶ ~5 kg of enriched isotope/module
 - ▶ 100 kg: 20 modules
 - ▶ ~ 60 000 channels for drift chamber
 - ▶ ~ 20 000 PMT
 - ▶ energy resolution $\Delta E = 2.6\% @ 3 \text{ MeV}$
 - ▶ efficiency: 40%
 - ▶ LNGS/LSM

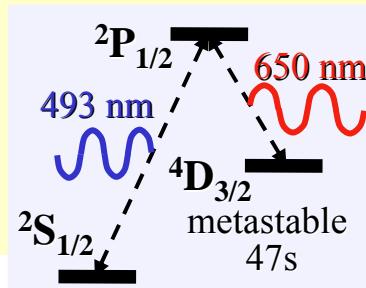
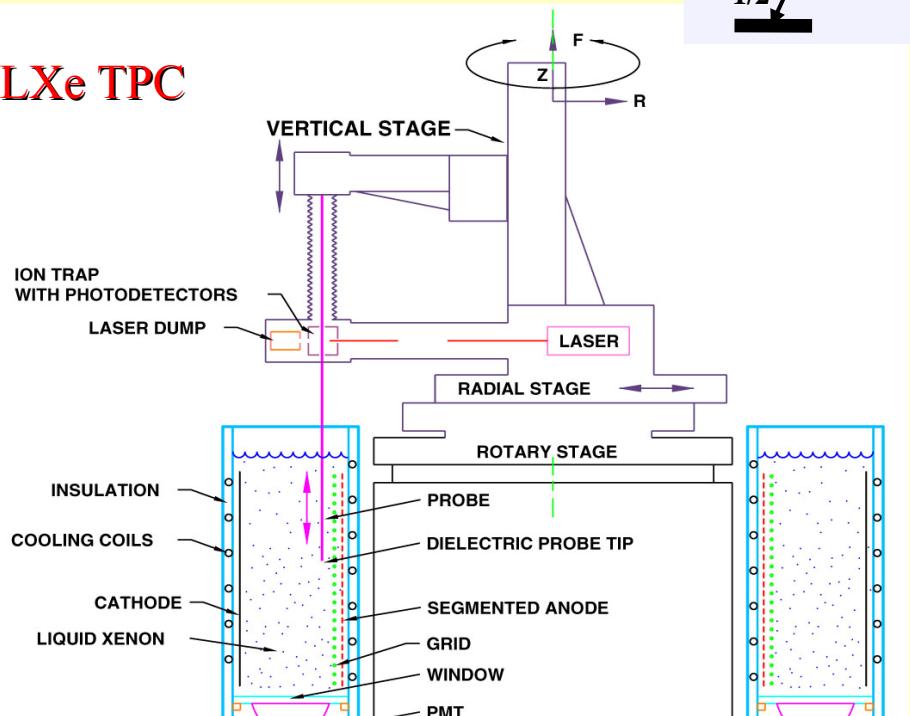
2006-2008: R&D
2009: first module
2011: all modules
2016: final results



EXO

- concept: scale Gotthard experiment adding Ba tagging to suppress background ($^{136}\text{Xe} + ^{136}\text{Ba} \rightarrow$ $+2\text{e}$)
- single Ba⁺ detected by optical spectroscopy
- two options with 63% enriched Xe
 - High pressure Xe TPC
 - LXe TPC + scintillation
- calorimetry + tracking
- expected bkg only by $\text{O}_2 - \text{H}_2\text{O}$
 - energy resolution $\Delta E = 2\%$

LXe TPC



Present R&D

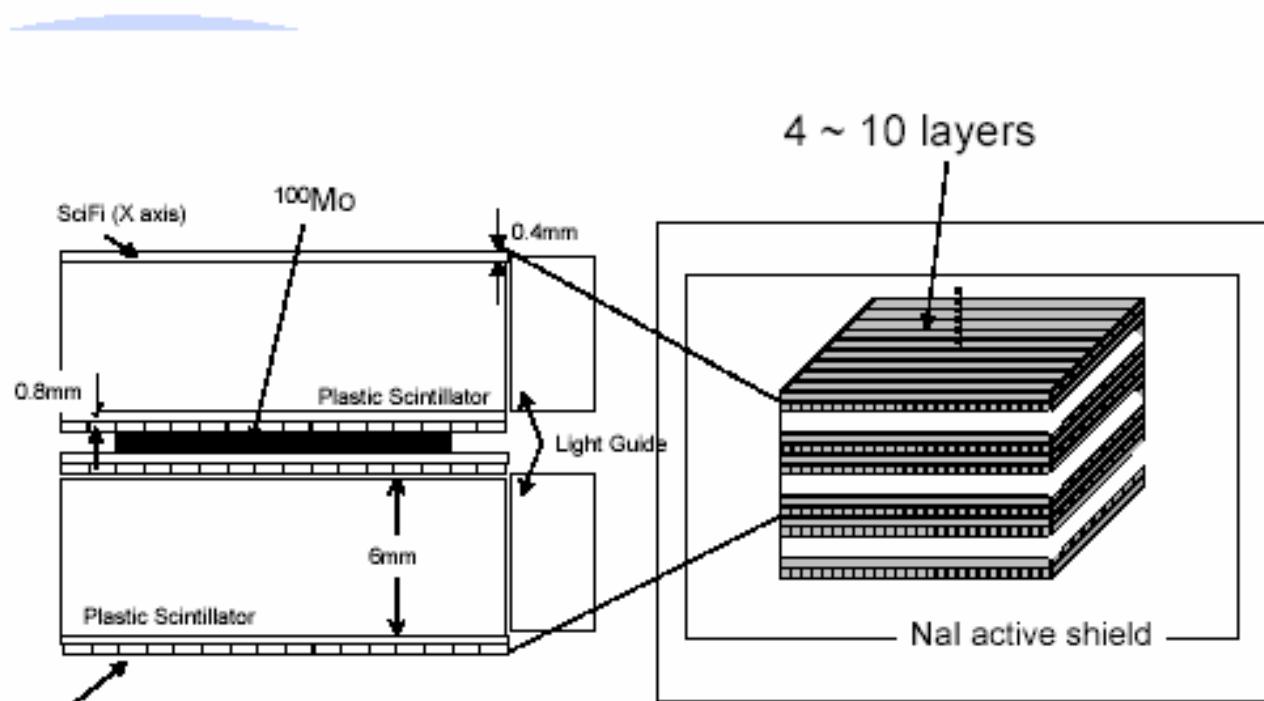
- Ba⁺ spectroscopy in HP Xe / Ba⁺ extraction
- energy resolution in LXe (ion.+scint.):
- Prototype scale:
 - 200 kg enriched L¹³⁶Xe without tagging
 - all EXO functionality except Ba id
 - operate in WIPP for ~two years
- Prototype goals:
 - Test all technical aspects of EXO (except Ba id)
 - Measure 2v mode
 - Set decent limit for 0v mode (probe Heidelberg- Moscow)

Full scale experiment at WIPP or SNOL

- 10 t (for LXe $\square 3 \text{ m}^3$)
 - $b = 4 \times 10^{-3} \text{ c/keV/ton/y}$
 - $\tau_{1/2} \square 1.3 \times 10^{28} \text{ y}$ in 5 years
 - $\langle m \rangle \square 0.013 \div 0.037 \text{ eV}$

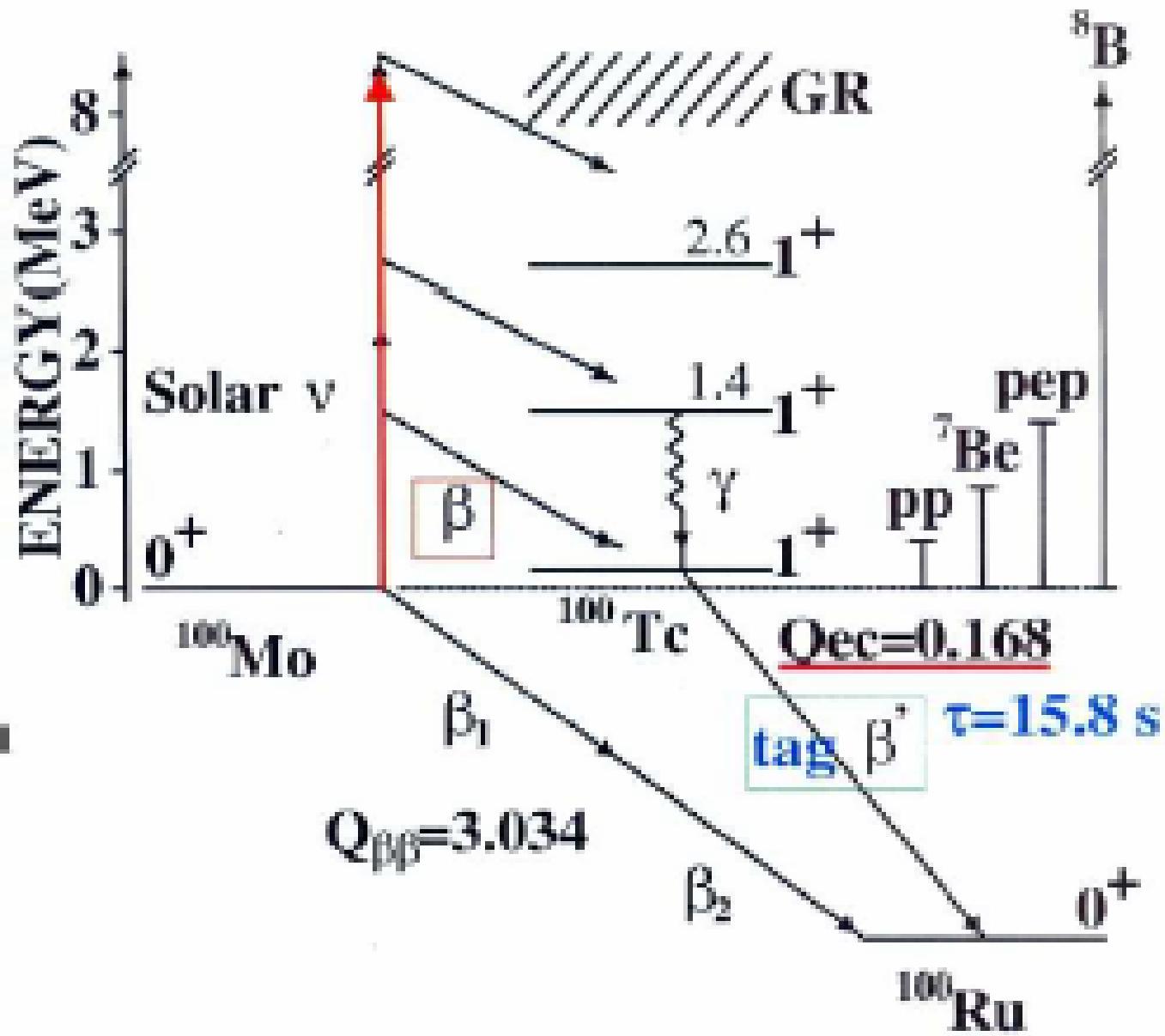
Tracking

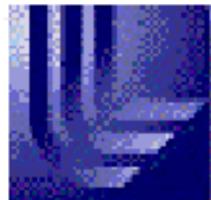
MOON



Size ; Plastic Scintillator ~ 50cm X 50cm

^{100}Mo foil ~ 30cm X 30cm





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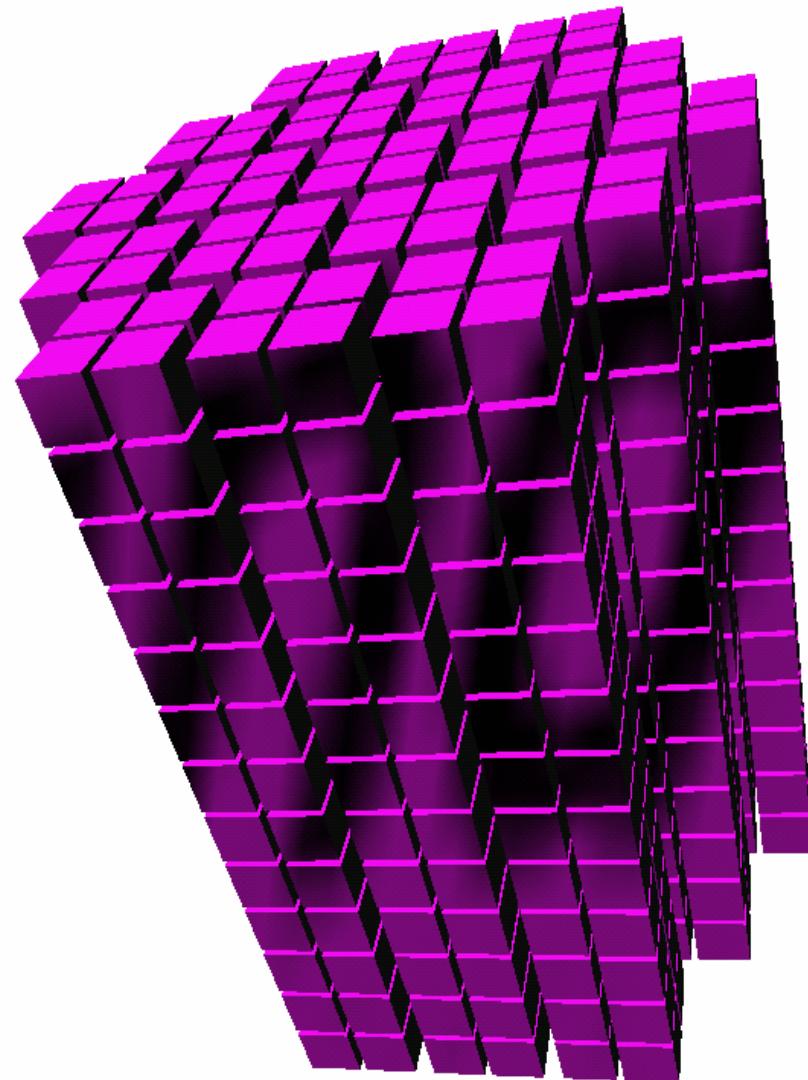
The CUORE project

(approved by the S.C. of Gran Sasso Laboratory and by INFN)

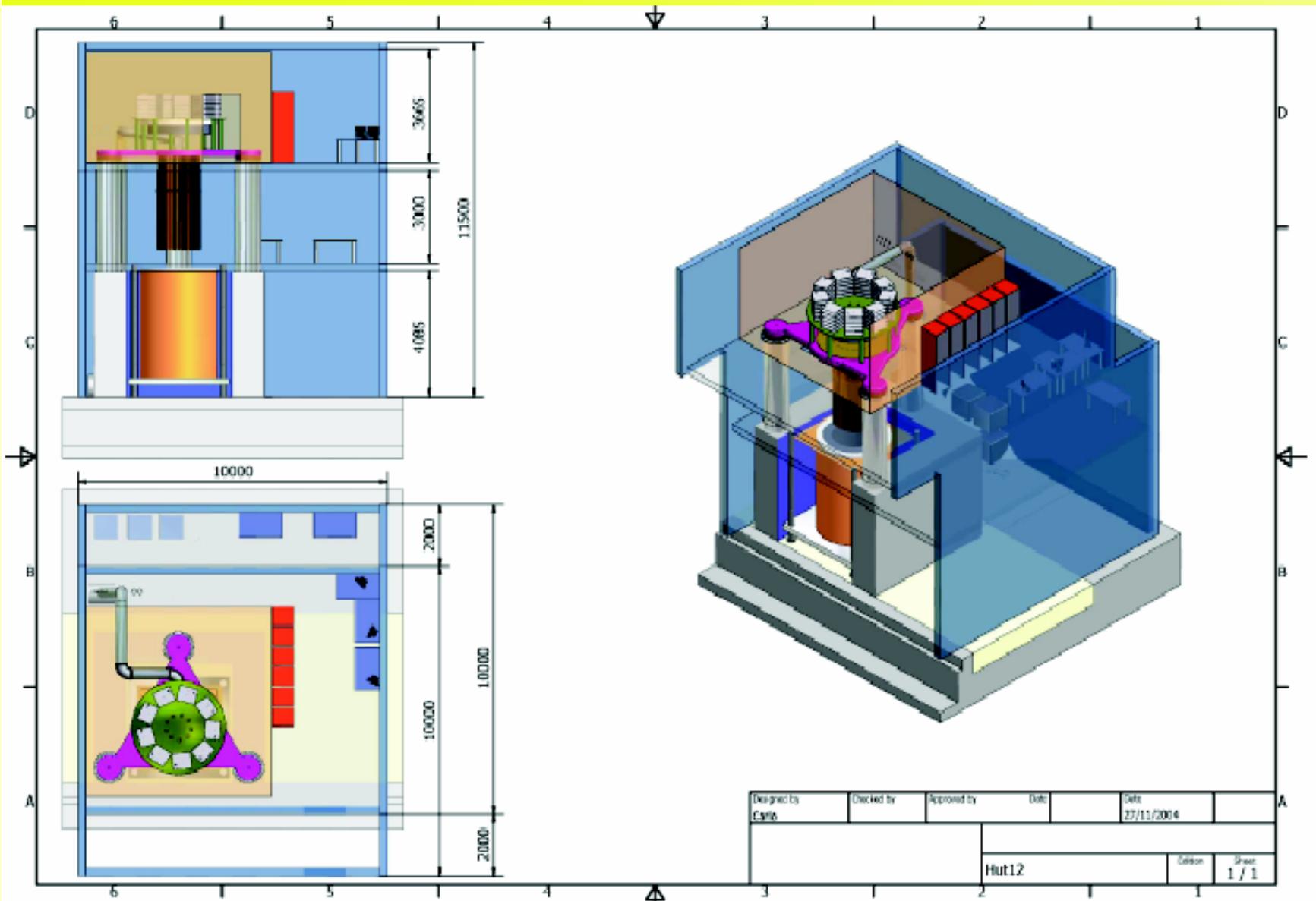
CUORE is an array of **988** bolometers grouped in **19** columns with **13** floors of **4** crystals

$$\begin{aligned} 750 \text{ kg TeO}_2 &\Rightarrow 600 \text{ kg Te} \\ \Rightarrow & 203 \text{ kg } ^{130}\text{Te} \end{aligned}$$

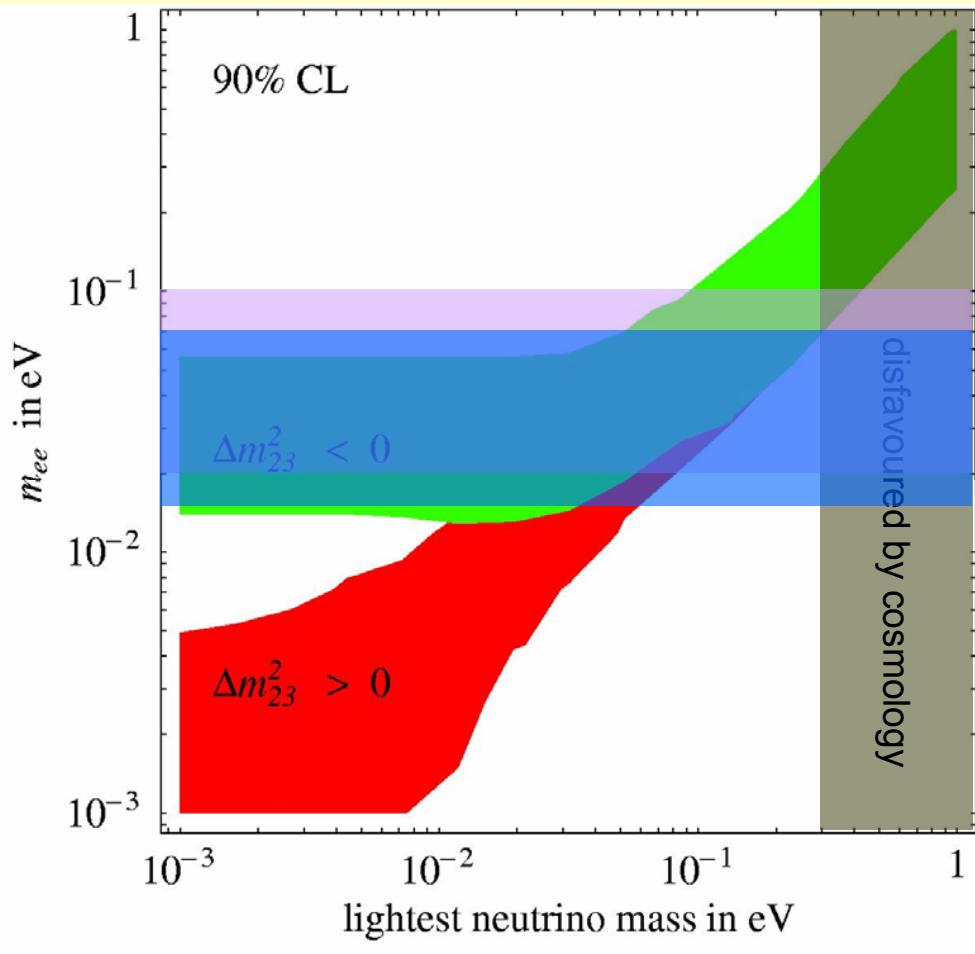
Crystals are separated by a few mm, only, with little material among them



CUORE hut



CUORE expected sensitivity



In 5 years:

b (counts/keV/kg/y)	Γ [keV]	$T_{1/2}$ [y]	$\langle m_\nu \rangle$ [meV]
10^{-2}	5	2.1×10^{26}	19-100
10^{-3}	5	6.5×10^{26}	11-57

Other possible candidates for neutrinoless DBD

Compound	Isotopic abundance	Transition energy
$^{48}\text{CaF}_2$.0187 %	4272 keV
^{76}Ge	7.44 "	2038.7 "
$^{100}\text{MoPbO}_4$	9.63 "	3034 "
$^{116}\text{CdWO}_4$	7.49 "	2804 "
$^{130}\text{TeO}_2$	34 "	2528 "
$^{150}\text{NdF}_3$ $^{150}\text{NdGaO}_3$	5.64 "	3368 "

- ^{130}Te has high transition energy and 34% isotopic abundance => enrichment non needed and/or very cheap. Any future extensions are possible
- Performance of CUORE, amply tested with CUORICINO
- - CUORE has been approved and has already an underground location
Dilution refrigerator already funded

CONCLUSIONS

The discovery of neutrino oscillations exists and Δm^2 is $\neq 0$

We need to determine the Majorana nature of the neutrino and the absolute value of $\langle m_\nu \rangle$

Neutrinoless double beta decay would indicate not only lepton number violation , but also $\langle m_\nu \rangle \neq 0$

This process has been indicated by an experiment (Klapdor) with a value of ~0.44 eV but not yet confirmed

Future experiments on neutrinoless double beta decay will allow to reach the sensitivity predicted by oscillations

Their peculiar multidisciplinarity involves nuclear and subnuclear physics , astrophysics , radioactivity, material science, geochronology etc